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The potential for renewable energy in industrial applications

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ABSTRACT

To date, insufficient attention has been paid to the potential of renewable energy resources in industrial applications. Our analysis suggests that up to 21% of final energy demand and feedstock-use in the manufacturing industry sector could be of renewable origin by 2050, a five-fold increase over current levels in absolute terms. This estimate is considerably higher than other recent global scenario studies. In addition, if a 50% share of renewables in power generation is assumed, the share of direct and indirect renewable energy use rises to 31% in 2050. Our analysis further suggests that bioenergy and biofeedstocks can constitute three-quarters of the direct renewables use in this sector by 2050. The remainder is roughly evenly divided between solar heating and heat pumps. The potential for solar cooling is considered to be limited.

While low-temperature solar process heat can reach cost-effectiveness today in locations with good insolation, some bioenergy applications will require a CO_2 price even on the longer term. Biomass feedstock for synthetic organic materials will require a CO_2 price up to USD 100/t CO_2, or even more if embodied carbon is not considered properly in CO_2 accounts. Future fossil fuel prices and bioenergy prices in addition to the development of feedstock commodity markets for biomass will be critical. Decision makers are recommended to pay more attention to the potential for renewables in industry. Finally, we propose the development of a detailed technology roadmap to explore this potential further and discuss key issues that need to be elaborated in such a framework.

Contents

1. Introduction

It is clear that renewable energy is a key tenant of sustainable development. Today renewable energy accounts for 13% of global primary energy use. This includes an 18% share of electricity generation, 10% of heating, about 30% of cooking (largely traditional biomass) and 3% of transportation fuels [14,16,26,30]. Renewables account for 9% of industrial energy use. Its use is growing rapidly, driven by rapidly growing demand, technology advances, cost reductions, supply security concerns and environmental concerns. Governments around the world share this vision. As evidence of this, 149 of them have established the International Renewable Energy Agency (IRENA), a new intergovernmental organization. The goal of this agency is to accelerate growth of renewable energy use worldwide across all sectors in order to meet policy targets for energy access, economic growth, energy security and environmental sustainability. Countries have agreed to develop

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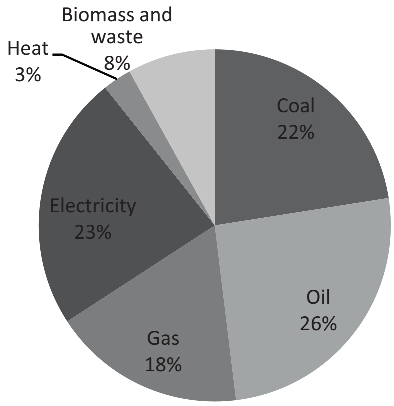

Fig. 1. Industrial energy mix in 2035, WEO 450 ppm scenario [14].

a roadmap for renewable energy in the industry sector [21]. The United Nations Industrial Development Organisation (UNIDO) is working in the demonstration and deployment of renewables in industry, including various projects in the area of solar heating and bamboo feedstock for energy and materials [36]. There is consensus that renewable energy use will grow significantly in the coming decades. For example the IEA World Energy Outlook 2010 (WEO) suggests that, by 2035, the use of renewables can grow to 27% of primary energy use [14]. By 2035, the IEA analysis sees the use of traditional and non-traditional bioenergy can double compared to 2008. In the current IEA new policies scenario industrial energy use is projected to grow from 98 EJ in 2008 to 156 EJ in 2035. In the 450 ppm scenario it rises only to 130 EJ in 2035 due to higher efficiency. This consumption excludes feedstock for the production of synthetic organic materials. Non-energy use for industry is projected to grow from 31 EJ in 2008 to 43 EJ in 2035 (excluding bitumen and lubricants). So inclusion of non-energy use raises industrial energy use by about one third. Industrial energy use in the WEO 450 ppm scenario in 2035 amounts to 168 EJ. When losses in electricity generation are considered, industry accounts for approximately one third of primary energy use in this scenario (Fig. 1).

Despite the optimistic overall outlook for renewables in the WEO 2010, the projections for industry are rather sobering. Only 8% of the total final energy use in this sector is of renewable origin, all of it is biomass. The WEO assumes no significant uptake of renewables for feedstocks and no significant direct use of other forms of renewable energy such as solar heating. In fact the share of renewables in this ambitious scenario is on par or slightly below the share of renewables in industry today.

These scenario results are consistent with other sources, including the IEA Energy Technology Perspectives [15]. They indicate that the prospects for renewable energy growth in general are good, notably in power generation, if proper ambitious climate policies are put in place. However uptake in end-use markets remains a concern and should be accelerated further. This paper assesses the options for industrial use of renewable energy, and outlines element of a roadmap to achieve this. (Production of electricity from renewable sources is outside the scope of this paper.)

2. Statistical issues

Renewables account for 9% of industrial final energy use. Within industry, bioenergy use dominates total renewable energy use. It includes use of residues in the wood processing industry and pulp and paper industry. Also significant amounts of bioenergy are used on traditional industries in developing countries. This category is not properly measured, which results in considerable uncertainties in the statistics.

While there is plenty of literature regarding the proper definition of renewable energy use for power generation, also for industry statistical issues exist that have not received the same level of attention. Wood is used as feedstock for pulp production. Wood is also used as a building and construction material, where it competes with other materials. Agricultural crops are used as feedstock for chemical products, notably so-called oleochemicals and natural fibres such as cotton.

We estimate that in the order of 12 EJ of biomass feedstock end up in industrial products that are not counted as renewable energy and feedstock use (700 Mt oven dry matter wood in 2009 plus around 50 Mt natural oils, natural fibres and starch) [8]. Only a small fraction that is incinerated with energy recovery is counted as energy use in the IEA energy statistics. In contrast 42 EJ of non-energy use of fossil fuels is included in the primary energy use, of which 31 EJ are used in industry.

If both renewable electricity use and biomass feedstock were accounted as described, the share of renewables in industry would be substantially higher [29]. We estimate that it would raise the share of renewables in industry to 18% in 2008. This would double the share of renewables. This is important as it suggests that renewables already play an important role today, which reduces the challenge for future growth.

3. Options and trends

Total fossil fuel and feedstock use in industry amounted to 117 EJ in 2008 (IEA Statistic Database, as of September 2010). This includes blast furnaces, coke ovens and non-energy use. Industrial use of fossil fuels can be split into:

- Heat – about 75 EJ of fuel yielding about 50 EJ of useful heat;
- Carbon and hydrogen for chemical reactions (iron making, ammonia) – about 12 EJ yielding 928 Mt iron (50–55% conversion efficiency) and 153 Mt ammonia (65–70% conversion efficiency);
- Carbon as feedstock for synthetic organic materials (plastics, fibres, bitumen, etc.) – about 30 EJ yielding 245 Mt plastics, 90 Mt other petrochemical products and 89 Mt bitumen.

We consider these market segments independently. The yields are important because they indicate significant losses in the transformation of fossil fuels into useful energy. The losses may be substantially different in case renewable energy is used. This paper analyzes the potential for renewable energy use primarily in four areas, namely:

- Biomass for process heat;
- Biomass for petrochemical feedstocks;
- Solar thermal systems for process heat; and
- Heat pumps for process heat.

Unlike combustible fossil fuels, not all of the required temperature levels can be provided by all of the renewable energy sources and technologies. Different types of biomass feedstock can cover the full temperature range required by industrial processes, including high temperatures. To achieve higher temperatures, preprocessing might be needed (i.e. from wood to charcoal, for use in blast furnaces).

On a laboratory scale it has been shown that solar thermal can provide temperatures above a thousand degrees Celsius, but in practice today this is limited to less than 150° for flat plate systems and less than 350° for parabolic trough collector systems [39]. However, in general, costs go up as the temperature level

rises. Especially for low temperature applications below 100° solar energy is a suitable option, even at moderate insolation levels [40]. The food and beverage industry is an example of such an application (e.g. dairies). Solar process heat use has been successfully demonstrated in a few hundred industries [5,23,24,37,42]. There is also increasing attention from developing countries, for example UNIDO has recently started demonstration projects in the Dairy industry of Western India and in the Ukraine, funded by the Global Environmental Facility (GEF). This solution is cost-effective in many cases: for example. Also direct of use solar drying is of interest, for example drying of tea has been successfully demonstrated [25].

The chemical and petrochemical industry is the largest energy consuming industry sector [12]. This industry requires significant amounts of heat (on the order of 11 EJ) at temperature levels between 100 and 400 °C. Modern Concentrated Solar Thermal (CST) plants are able to deliver heat at such temperatures, however this heat is not cheap. A typical Concentrated Solar Power (CSP) plant for power generation will cost USD 5500–6500 per kW (with storage system and power block) and may reach 25% electric efficiency (more with gas co-firing). About half of the cost is for the solar field [43]. If such a plant would produce medium temperature steam in sunny climate zones such as the Middle East, with a 50% capacity factor and 10% capital cost, the heat delivered would cost around USD 10/GJ. Perhaps cogeneration would reduce the cost further. However to date there is no development in this market segment, as cost are significantly higher than for fossil fuel. Lower cost solar fields would be needed. It is projected that these cost can be reduced by a third in the coming decade [28]. Also space is a concern and may limit uptake for existing plant: a 200 MWth solar field covers 50 ha.

In high temperature heating applications such as brick making, ceramics, lime or cement kilns, use of biomass and other alternative fuels for co-firing is widely spread and cost-effective [17]. These industries require in the order of 17 EJ of heat. The temperature levels are above 1000°, a level that cannot be reached with conventional biomass combustion. Therefore co-combustion and/or oxygen enrichment are needed for high shares of biomass and refuse derived fuel.

Iron making requires carbon for the chemical reaction. Ammonia is produced by reaction of hydrogen with nitrogen in the air. Biomass is the only source of renewable carbon. Charcoal is still widely used for iron making in Brazil, where it is cost effective at about 200 USD/t [32]. High coking coal prices make this option also increasingly attractive elsewhere. Some work is ongoing to enhance charcoal making processes. Current total global charcoal production equals about 10% of the coal and coke use for iron making. There is no option to make ammonia directly from renewable energy. Either biogas can be used (which is not available in large amounts – less than 1% of global gas production is biogas, while ammonia production accounts for 5% of global gas consumption), or a more costly process that uses electricity. Interesting attempts are ongoing for direct nitrogen fixation by plants, an innovative route for greening of industry. However this is not elaborated further as it extends beyond energy substitution.

Biomass can be used for the production of plastics and fibres [4,41]. Olefins (ethylene, propylene) are the two main basic building blocks, the basis for nearly half of all petrochemicals. Production of ethylene from ethanol has started in Brazil on a commercial scale (300 kt/year) [2]. Worldwide about 68 Mt of ethanol were produced in 2010, in comparison with 115 Mt of ethylene. The production of this amount of ethylene would require 193 Mt of ethanol, three times current world ethanol production. Another option is production of methanol from biomass followed by methanol-to-olefins. This route is not yet applied but the two separate steps are proven and demonstrated on a commercial scale today [3].

Aromatics (benzene, toluene) constitute another group of basic building blocks. Lignin, a by-product of paper making, contains significant amounts of compounds with a similar chemical structure. Efforts are ongoing to extract and use these, but so far there are no commercial applications. Analysis suggests that a technical potential exists to replace 90% of all feedstocks for petrochemical with biomass [6,33]. In addition, various solvents such as butanol can be produced through fermentation, but this is not yet done on a large scale.

New applications for industrial biomass use have emerged in the last decade. These include: biomass gasification for process heat in countries such as China and India, the use of biogas from digestion of residues in the agro-food industry. Production of biogas from industrial and agricultural residues is rising, Europe alone produced around 0.35 EJ of biogas in 2009 [7].

4. Potentials

This section explores the potentials for the principal categories of RE.

4.1. Biomass

Overall, technical options exist to replace perhaps half of industrial energy and feedstock use with renewable energy. However cost poses an obstacle in many cases. While successful demonstrations have occurred in the SME sector, large industry generally does not consider renewables as a viable option. Biomass emerges as a key resource. The problem is the uneven distribution of this resource, and the fact that biomass can also be used in other energy markets. Low cost transportation and standardization are essential. Therefore the emerging markets for pellets and torrefaction (carbonization) deserve attention. Also ethanol as feedstock for chemical products can be easily transported.

An in depth analysis of literature [1,10,11,34,35] in the field of biomass feedstock cost estimations resulted in the definition of a supply cost curve for the biomass feedstock, distinct between energy crops and residues (Fig. 2). The estimated long term supply cost for biomass has to be considered as delivered at the point of use, including cost, insurance and freight (CIF). Prices may differ from supply costs given the volatility of commodity prices, the non-liquidity of many regional biomass markets and the absence of true global markets for biomass trading. These figures should be considered as a lower bound of cost for the actual price of different biomass commodities.

We assume a 150 EJ global potential for available biomass feedstock, well within the range of other recent potential studies of 50–1500 EJ [19]. The supply curve assumes that one third of all bioenergy resources would be available for industrial use.

The complexity of bioenergy in terms of supply uncertainty and a wide range of markets for a scarce resource make planning very complex. This poses also an important planning problem and acts as an inhibitor for rapid development. As industry already uses significant amounts of bioenergy the sector is well positioned to expand further in this direction.

Reference prices for coal and natural gas are also indicated, assuming no price for carbon. These reference prices should be considered as a lower bound, as CO_2 pricing could raise these levels considerably.

Within industry, the question is if scarce biomass resources should be used for energy or as feedstock for materials. Today for example in Europe significant policy incentives exist to use biomass in CHP plants, while materials applications are not promoted. This results in a distorted competition.

Use of industrial residual biomass for heating purposes is widely spread in industry and is cost-effective today. There are few

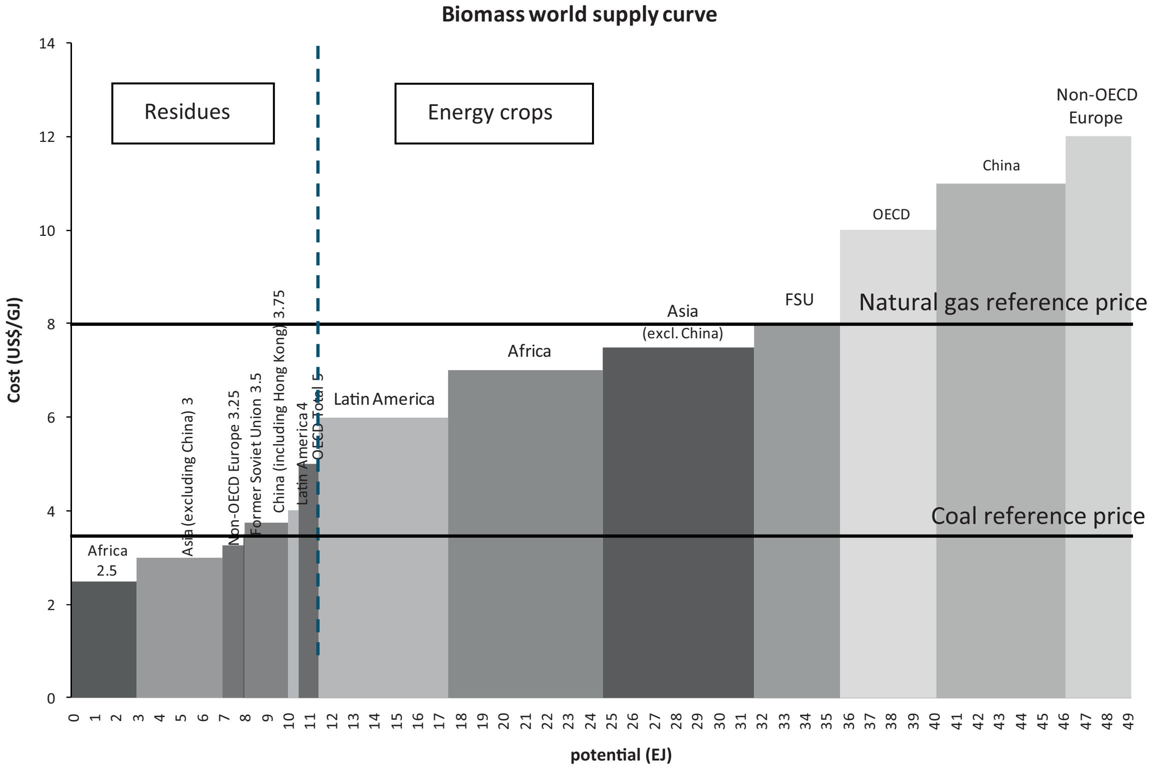

Fig. 2. World biomass supply cost curve for industrial process heat production, 2050 (UNIDO analysis). Natural gas reference price.

instances of dedicated energy plantations for industrial use in operation today, or where harvesting wood from forests for industrial boilers is economic. If a CO_2 price will be introduced, this situation could change, especially where biomass competes with coal [33].

As an example of biomass feedstocks competitiveness with fossil feedstock, the case of the production of ethylene from ethanol is relevant as it is currently practiced on a commercial scale. 1.68 tonnes of ethanol are needed per tonne of ethylene. At an ethanol price of USD 0.5/l (Brazil in 2010), the feedstock cost would be USD 1050/t and the ethylene production cost would amount to USD 1350/t. In comparison, feedstock cost for ethylene at an oil price of USD 100/bbl amount to USD 740/t ethylene and the production cost amount to USD 1300–1400/t. The numbers suggest that biomass feedstocks can be commercially attractive today, but low biomass feedstock cost is essential. Low ethanol prices and high gasoline prices is an unlikely combination on the long term: as oil and gasoline prices rise, ethanol prices are likely to rise as well. An oil price of USD 100/bbl implies gasoline production cost of USD 0.8 per litre. If ethanol is sold at the same price, a carbon price will be needed to make bioethylene commercially attractive. The height of this price will depend on the carbon accounting practice for the petrochemical reference. Today only direct process emission are considered, carbon stored in materials and products that is emitted as CO_2 in waste incinerators is not counted. This makes a difference between 1–2 and 4–5 t CO_2/t ethylene, or a difference between USD 250–500 and USD 100–120 CO_2 price for commercial bioethylene. Carbon accounting for synthetic organic deserves special attention as it may affect the economic feasibility of biomaterials substantially; this is an area that deserves more policy attention.

4.2. Solar thermal

Solar thermal energy has the potential to contribute 5.6 EJ/year to industrial energy use by 2050. Almost half of this is projected to be used in the food sector, with a roughly equal regional distribution between OECD countries, China and the rest of the world, mainly in Latin America (15%) and Other Asia (13%). Costs depend heavily on radiation intensity and are projected to drop by more than 60%, mainly as a result of learning effects, from a range of USD 17–USD 34 per gigajoule (GJ) in 2007 to USD 6–USD 12/GJ in 2050.

An analysis of several sources (a summary in [13]) suggests the current generation and investment costs for different configuration and radiation levels shown in Table 1.

This shows that, where good solar radiation is available, solar thermal technologies for industrial process heat are very close to break-even today. Table 1 shows average figures for four representative cases. Where seasonal variation is not large, seasonal storage is generally not needed. In some regions where seasonal variation is very important in terms of reduced radiation in winter for several months, seasonal storage may improve the economic performance of the system. Where solar radiation is very favourable (2000 kWh/m^2/year in the example), solar cooling technologies can be considered as an option that matches the maximum productivity of the solar system with the maximum cooling demand. These four cases are representative of different solar radiation situation and system configuration.

In many specific cases where the cost of the reference energy unit is higher or where locally manufactured solar thermal systems are cheaper, solar thermal technologies are already cost effective without any need for subsidies. In areas with lower solar radiation, such as in central Europe, solar thermal technologies need substantial cost reductions to become competitive. In some specific markets, taxes on fossil fuels or subsidies for renewable energy make solar thermal competitive already today even in areas of low solar radiation. Although solar cooling is still in an early demonstration stage, in countries with stable solar radiation and unstable, expensive electricity, solar cooling may become a viable alternative to electric chillers in the next 10 years.

Table 1
Investment and generation costs for solar thermal for industrial process heat—2007 and 2050.[a]

	Insolation	Heat storage/cooling		2007		2050	
				Generation cost [USD/MWh]	Investment cost [1000 USD/MWh]	Generation cost [USD/MWh]	Investment cost [1000 USD/MWh]
Case 1	2000 kWh/m^2/year	Daily storage	Actual/projected	57	450	21	170
			Break even	50	397	50	397
Case 2	1200 kWh/m^2/year	Daily storage	Actual/projected	94	450	36	170
			Break even	50	238	50	238
Case 3	1200 kWh/m^2/year	Seasonal storage	Actual/projected	90	765	34	289
			Break even	60	508	60	508
Case 4	2000 kWh/m^2/year	Including cooling	Actual/projected	137	1450	52	549
			Break even	80	847	80	847

[a] Assuming, based on IEA data on capacity and production, a world average load factor for 2007 of 605 full load hours/year, a 7% interest rate, and a capital recovery factor of 9%. O&M costs, in USD/MWh/year, are 2.5% of the ratio between investment costs and full load hours.

Table 2
Breakeven analysis and learning investments for solar thermal in industry.[a]

	Insolation	Heat storage/cooling	Break-even capacity [GW]	Learning investments for reaching break-even [bln USD]	Subsidies [bln USD]
Case 1	2000 kWh/m^2/year	Daily storage	252	34	2
Case 2	1200 kWh/m^2/year	Daily storage	1235	320	67
Case 3	1200 kWh/m^2/year	Seasonal storage	609	264	41
Case 4	2000 kWh/m^2/year	Including cooling	908	769	144

[a] This table is based on the same assumptions and calculation methodology as Table 4. The full load hours (in h/year) for the four cases are: 750, 450, 800 (with the benefit of seasonal storage) and 1000 (benefiting from a good match between the load curve for cooling and peak production from solar thermal systems).

The cases describe different levels of insolation and different storage approaches. As with other technologies, there are advantages in deploying early systems where they are most effective, i.e. initially on simple systems in areas with abundant solar radiation. Such deployment is already cost effective today. As further investments are made, the cost of solar thermal systems should decline, making them progressively more cost-effective in other less favourable conditions. Table 1 also shows the cost projections for 2050, based on learning curves. These learning curves, observed for many energy technologies, show a constant percentage cost reduction per doubling of installed capacity. The percentage is technology specific but constant over a long period. See for example [22].

At the current learning rate of 20% [13], solar thermal would be expected to break even in most potential applications, even in temperate climates using seasonal storage for solar cooling. One can argue if solar thermal is a single technology. For higher temperature applications significant spill-over effects from CSP power generation are likely. On the low temperature end of the range, spill-over effects from the domestic and commercial heating market are likely.

To achieve the projected 5.6 EJ/year in 2050, the solar capacity needed by the industrial sector would be over 2500 GW thermal (GWth) capacity, assuming current levels of full load at around 600 h/year and that learning effects are achieved only in the industrial sector (no spill-over effects). Depending on the lifetime of the systems and on the rate of their diffusion, the total cumulative capacity that will need to be installed by 2050 would be in the range of 3500 GWth. Given that, in 2009, the total global capacity of solar thermal installations was only 180 GWth, this will require a major investment programme. In Table 2, the learning investments are calculated for each case separately, assuming that learning will only occur for that that single technology under similar insolation conditions.

Depending on the solar system configuration, learning investments range from 34 to 769 billion USD and subsidies (additional cost compared to incumbent technology) range from 2 to 144 billion USD (Table 2). A policy that first focuses on "simple" niche markets for heating with daily storage and gradually moves into seasonal storage and cooling seems substantially more cost-effective. International cooperation is warranted with an initial focus on heating demand in sun-rich countries where break-even will be reached much earlier.

4.3. Heat pumps

Heat pumps also have a part to play in low temperature process applications and are estimated to contribute 4.9 EJ/year in 2050. Most (43%) of this will be concentrated in the food sector, mainly in OECD countries (60%), China (16%) and the Former Soviet Union (15%). Costs for useful energy supply are projected to drop by between 30% and 50%, due mainly to reduced capital costs, increased performance and more consistent, market driven, international electricity prices, from a range of USD 9–USD 35/GJ in 2007 to USD 6–USD 18/GJ in 2050.

The cost of useful heat from heat pumps depends very much on the temperature required, as the larger is the increase in temperature required, the lower is the efficiency that can be achieved. There are ongoing efforts on the technology side for designing optimized heat pumps for industrial process heat. However, the main physical law behind it is unavoidable. For this reason, heat pumps are most suitable for increasing the temperature of a waste heat stream, to upgrade it to useful process heat.

Assuming that the large part of the heat pumps for industrial applications will be electric powered,[1] the most important cost component of the useful heat produced would be the price of electricity. The analysis has been conducted based on the IEA Energy Prices and Taxes, Electricity End-Use Prices for industry. As of today, the differences in electricity prices among different regions are still substantial, but we expect them to narrow with time. In Table 2 we present the cost per GJ of useful energy from heat pumps, which

[1] The cooling demand is not covered in this section. Cooling can be effectively provided also with thermally driven chillers (absorption and adsorption technologies). See Ref. [36, chapter III.b].

Table 3
Useful energy cost for heat pump systems.

USD/GJ of useful energy	2007		2050	
	Below 60 °C	60–100 °C	Below 60 °C	60–100 °C
Africa	15	22	8	12
China	9	13	6	9
Former Soviet Union	15	22	13	19
Latin America	13	20	8	11
Middle East	13	19	7	10
Non-OECD Europe	24	35	12	18
OECD total	18	27	12	17
Other Asia	21	30	9	13

results from our analysis. The two temperature levels are representative of the increase in temperature requested to the heat pump, rather than absolute output temperature. However, we are addressing the two low temperature levels defined in our analysis building the supply cost curves based on this figures. These figures are typical but conditions within the specified regions vary widely.

The cost figures are based on air source heat pumps, which are not necessarily the best option, especially when waste heat streams are available or where the ground or water temperatures are on average higher than air temperature. As for solar thermal, the economics of heat pumps in industrial applications depend on site specific factors. Even more specific than solar once we consider the different waste heat streams that need to be identified through an appropriate system optimization analysis of industrial plant, using techniques such as pinch analysis, cascading heat use and optimizing the heat flows through high-efficiency (low-delta T) heat exchangers.

For the purpose of this analysis, a regional approach, instead of a site specific one, had to be used, to provide some general figures on the potential of heat pumps at the world level. This analysis should be intended as a way of highlighting the untapped potential, which should then be evaluated in detail for each individual industrial site with its own specificities.

The following table has been built based on author's elaboration on the IEA Energy Prices and Taxes database, choosing a representative country for each region, in terms of electricity price for industrial users in 2007. For the 2050 electricity price, a convergence towards 20 USUSD/GJ has been assumed, keeping a spread between regions (i.e. 12 USUSD/GJ in China vs. 24 USUSD/GJ in OECD).

The Seasonal Energy Efficiency Ratio (SEER) has been assumed as increasing one point between 2007 (SEER 2-3) and 2050 (SEER 3-4). The spread in terms of SEER between low (<60 °C) and mid-low temperature (60–100 °C) has been maintained constant, because the temperature increase requested is the main driver of the performance achievable by a heat pump (Table 3).

Competition among different renewable energy technologies for process heat production has been taken into account, looking in detail at the economics for several different aggregated regions.

Subsidies to fossil fuel constitute one of the paramount barriers to the deployment of renewable energy that we are facing today [14]. The competitiveness of renewables with fossil fuels is strongly dependent on national conditions and on fluctuations of energy prices in international markets. According to the IEA Energy Prices and Taxes database, between 1998 and 2009 natural gas end-use prices for industry were at a minimum in 2000 of USD 0.4/GJ in the Russian Federation and at a maximum in 2008 of USD 22.8/GJ in Hungary, varying by a factor of almost 60. At the end of 2009, the ratio between the lowest and the highest natural gas price for industrial end-use was around 10, from USD 2.1/GJ in Kazakhstan to USD 22.8/GJ in Denmark.

Similarly, coal prices varied by a factor of 30: from a minimum of USD 0.3/GJ in Kazakhstan in 2003 to a maximum of USD 10.1/GJ in 2008 in Switzerland. At the end of 2009, prices differed by a factor of almost 15, between USD 0.6/GJ in Kazakhstan and USD 8.7/GJ in Austria.

With a liquid, effective and efficient carbon market in place, the price of CO_2 would be one of the main factors in determining the success of renewable energy and the mix of fossil fuels. A CO_2 price of USD 100/t would raise coal process heat cost by 10–12 USD/GJ and this of gas by 6–8 USD/GJ. In the short term, the existing plant infrastructure is a significant barrier to price-driven fuel switching. But in the longer term, if prices stabilise on the carbon market and major energy consumers become more directly involved, more carbon intensive fuels such as coal will see their role reduced in favour of less carbon-intensive fuels such as natural gas and renewables. Biomass, through pre-processing technologies, will offer the only short term option for coal substitution without any replacement of the existing equipment, especially in sectors where the carbon content of the fuel is fundamental to the industrial process such as in the iron steel and chemical and petrochemical sectors.

Fossil fuel prices and bioenergy prices are the key factors that will determine the economics of renewables in the industry sector, and these will depend on a range of factors, notably energy and greenhouse gas mitigation policies across the world.

5. Scenarios

For the three different renewable energy sources, several different methodologies have been used to explore their potential. For biomass process heat, the existing level of deployment is sufficient, especially in certain sectors like pulp and paper and wood products, to evaluate the potential using the Logistic Substitution Model developed by IIASA [27] (Fig. 3). The IIASA scenario M of the Global Energy Assessment (GEA) was used for the demand projection [20].

Using the Logistic Substitution Model (LSM), countries that have historical data showing significant deployment of biomass in some sector can infer the shape of the logistic curve which represents the evolution over time of the share of biomass in the final energy consumption of that sector. Other countries or regions for which deployment has not yet started in a significant manner do not provide sufficient historical records to allow the model to forecast the deployment path of that energy source in that sector. For those sectors in those regions, which have no evidence of increasing and significant deployment of biomass, no deployment has been assumed by 2050. As policies may change the scenario, deployment may actually happen even in those sector and regions for which we estimated no potential. However, at the current stage, there is no evidence of this happening. The value added of this analysis is the fact that the potential for biomass has been evaluated based on ongoing deployment trend, instead of linear extrapolation of the average or latest growth rates, but rather assuming a logistic path that the share of biomass is already following. This approach has proven itself successful in several studies conducted, for the energy sector in particular [27].

The first account of the use of the logistic function to describe growth phenomena is by Verhulst in 1838 [44]. A relevant justification for the use of the LSM in the case of biomass substitution in industrial processes comes, before Marchetti and Nakicenovic, from Fisher and Pry in 1970 [9]. They argue that once the substitution of the new for the old reaches a few percentage points, it will proceed along a logistic substitution curve, defined as:

$$\frac{f}{1-f} = \exp(\alpha + \beta)$$

where f is the market share of the new entrant, t is the time unit, α and β are constant calculated from the historical time series data. They have shown the applicability of this approach on several industrial sectors and related technologies.

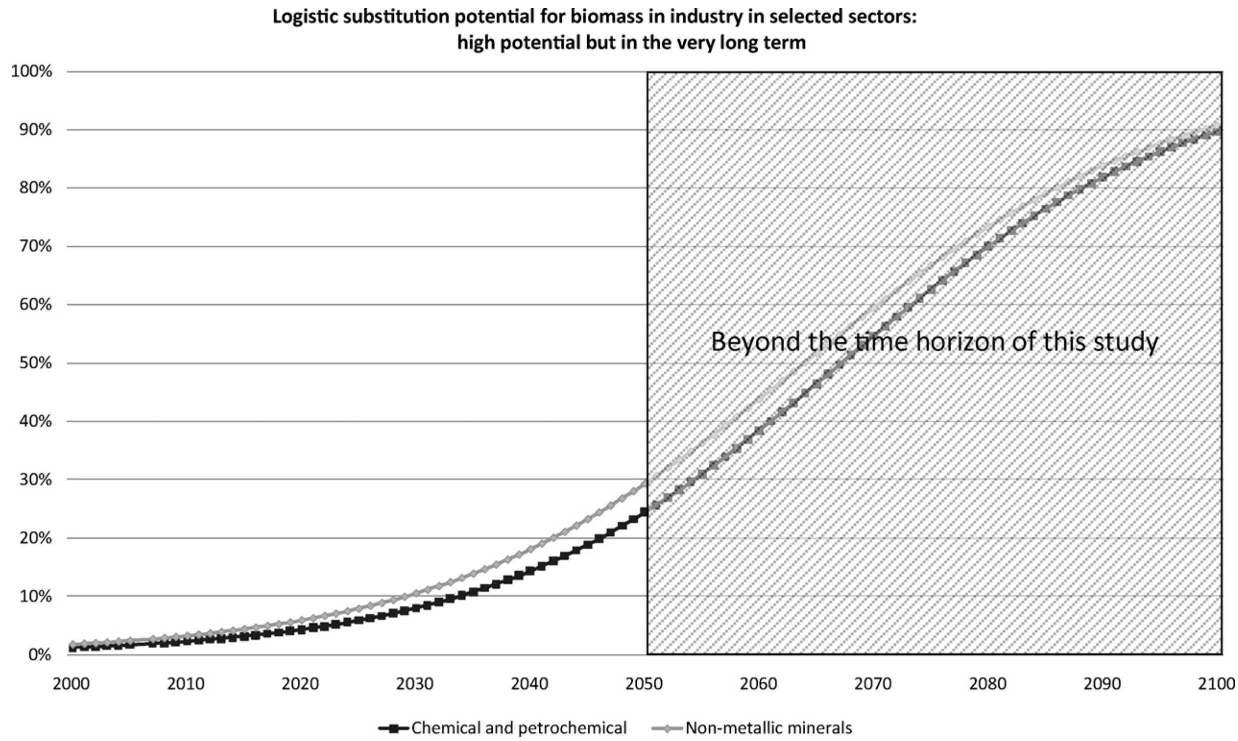

Fig. 3. Logistic substitution of biomass in the chemical and petrochemical and cement industries.

Marchetti and Nakicenovic apply this approach, generalizing it to n competitors, including a declining phase once a new competitor takes over the market share from the previous growing one, to the energy sector, applying it to 300 cases [27]. The testing has been undertaken for three classes of data: world data on primary energy sources; national or regional data on primary energy sources; and energy use in specific sectors. This is justifying the use of this methodology for the present study: we cover 12 industrial sectors from the primary energy source point of view, developing a forecast of the substitution potential for biomass only where it currently reaches the few percentage points demonstrated by Fisher and Pry as the necessary condition for a successful application of the logistic substitution equation to forecast the market share of a new entrant. Biomass is the major new entrant primary energy source in the industrial sector (Fig. 3).

The same approach has not been used for solar thermal or heat pumps, as the current level of deployment is insufficient to infer an ongoing logistic development path, unlike for biomass where the current share is sufficient in many regions and sectors to obtain realistic results through the Logistic Substitution Model.

Regarding solar thermal and heat pumps, the main substitution driver is the temperature range the technology can provide. With current technologies, several sectors have been investigated in the literature to define a portion of their heat demand at different temperature levels [18,31]. For some regions, CST was included able to provide temperature in the middle range (100–400 °C). In the low temperature range, heat pumps and solar thermal compete, based on regional, national and local conditions. For the purpose of this analysis, the geographical parameter was set to eight regions. The most representative country within each region has been used as a regional reference for electricity prices and solar radiation in order to define the share of low-temperature heat that would be likely supplied by either solar or by heat pumps based on an economic comparison of the cost of useful heat.

For biomass interregional trade has been considered. As the biomass quality became more consistent and the supply becomes more reliable, intercontinental trading of biomass for energy purposes is already happening. The higher the energy density of the biomass commodity, the cheaper, the more environmentally friendly and the easier its long distance shipping. For example, fully hydrophobic bio-coal could make direct use of the existing overseas shipping and delivery infrastructure for coal. The shipping of similarly large volumes of wood chips, however, would require the adaptation of existing energy transport facilities and would be considerably more expensive in terms of the amount of useful energy moved.

In the cement sector, around 3% of final energy consumption comes from biomass [17], although the situation varies widely by region. In Brazil, 35% of the final energy in the non-metallic minerals sector comes from biomass. But in China, where more than 50% of the world's cement is currently produced, more biomass would be needed to meet 35% of the total final energy demand of the sector than could be produced sustainably at a national level. Brazil can achieve its 35% share of biomass in the non-metallic minerals sector with 0.2 EJ. To do the same in China would require 1.7 EJ of biomass, or most of the biomass residues available in the country (according to the biomass feedstock supply cost curve developed in this analysis).

In the chemicals and petrochemicals sector, no countries use biomass for energy yet on a significant scale. Worldwide, biomass contributed 0.6% of the final energy use in the sector in 2007. Integrated biorefineries may offer the prospect of the wider use of biomass for the co-production of plastics, fuels and energy. Depending on the catalysts used, synthetic natural gas (SNG), hydrogen and liquids can be produced from biomass which, through methanisation, de-hydration or Fischer-Tropsch processes can be turned into fossil-substitute products. For example, ammonia and methanol can both be produced from SNG in much the same way as they are currently produced from fossil natural gas.

The main limits to the further penetration of biomass in the chemicals and petrochemicals industry are the availability of sustainable biomass resource and its economic competitiveness. Local

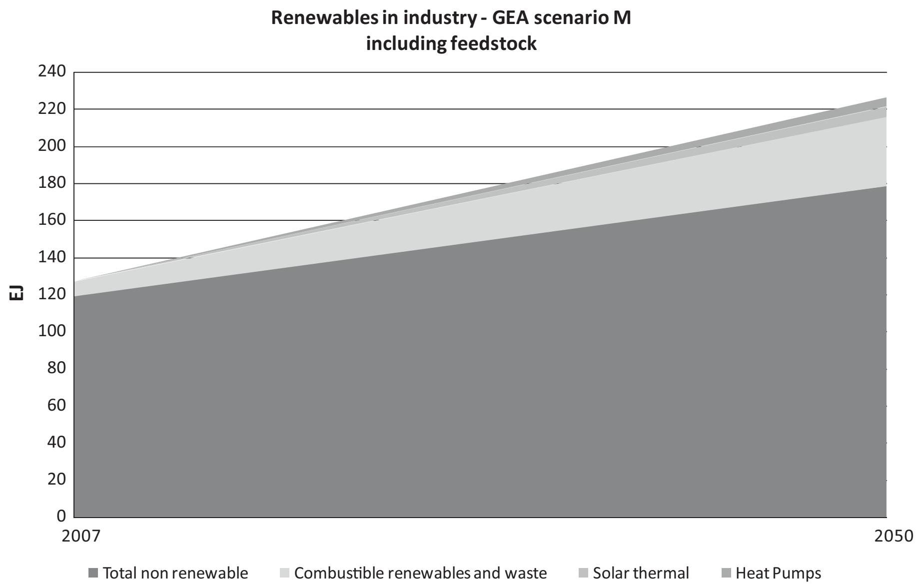

Fig. 4. Renewables potential in industry by 2050—final energy and feedstocks. UNIDO analysis.

availability has so far been the most critical constraint. The overcoming of this barrier through the development of international biomass energy markets will be heavily dependent on the emergence of an effective transformation sector that can turn biomass from a locally procured “alternative” fuel into a modern energy commodity.

Altogether, about 23% of the total final energy use in industry, excluding feedstocks, can be of renewable origin by 2050. This excludes the use of electricity produced from renewable resources for industrial use. In addition, up to 14% of the fossil feedstock expected to be used by industry can be substituted with biomass. Taken together, the potential exists to replace 21% of the final energy and feedstock energy expected to be used by industry in 2050 with renewables.

This study suggests that renewable energy use in industry has the potential to grow from less than 10 EJ a year in 2007 to almost 50 EJ a year in 2050 (Fig. 4). This equates to a growth from 8% to 21% of total final energy use.

In absolute terms, 70% of this potential growth comes from the greater use of biomass and wastes, with smaller contributions from solar thermal technologies and heat pumps. Bio-feedstocks constitute 7 EJ/year out of the total of almost 50 EJ/year primary biomass used as industrial feedstocks in 2050, while biomass for process heat accounts for over 30 EJ/year. Across all industrial sectors, biomass has the potential to contribute 37 EJ/year final energy. But the achievement of this potential will depend on a well-functioning market and on the development of new standards and pre-processing technologies. About one-third of the potential (12 EJ/year) could be achieved through inter-regional trade of sustainable biomass feedstocks.

Solar thermal is estimated to contribute up to 5.6 EJ/year. Although not part of the scenario considered here, the application of concentrating solar power (CSP) technologies in the chemical sector could potentially increase the contribution of solar thermal to 8 EJ/year. Heat pumps will compete with solar thermal technologies for low-temperature process heat applications, depending on electricity prices and the availability of solar radiation. The estimated potential for heat pumps in 2050 is 4.9 EJ/year.

In addition to the direct use of renewable energy, if a 50% share of renewables in power generation is assumed, the share of direct and indirect renewable energy use rises to 31% in 2050. Some industries, for example aluminium smelters, choose their site based on the availability of cheap energy, including hydropower. Forestry based industries and agricultural feedstock based industries also choose their location close to their resource base. In the future if renewable energy and feedstock use gains importance this could broaden to other industry sectors and other forms of renewable energy. This relocation option is an important advantage for uptake of renewables in this sector.

Table 4 provides a breakdown of the share of renewable energy by industry sub-sector. For biomass and feedstocks (non-energy use), the chemical and petrochemical industry, non-metallic minerals and pulp and paper dominate. No significant uptake has been assumed for example in iron and steel making. If CO_2 capture and storage in this sector does not take off, use of charcoal or electricity from renewables in this sector would have to rise, which would raise the overall share of renewables in industry even further. For solar and heat pumps sectors with low temperature heat demand dominate: feed and tobacco, machinery, mining and quarrying, textile and leather and transportation equipment. The fact that no solar heat application is assumed for the chemical and petrochemical industry is a conservative estimate. In the coming 5 years the annual installed capacity for CSP is projected to grow well above 1 GW and there could be significant spill-over learning effects from this sector for process heat in the temperature range of 200–500 °C.

Overall, an increase in renewable energy in industry has the potential to contribute about 10% of all expected GHG emissions reductions in 2050. At nearly 2 Gt of CO_2, this represents 25% of the total expected emission reductions of the industry sector. This is equivalent to the total current CO_2 emissions of France, Germany, Italy and Spain, or around one-third of current emissions in the United States [38].

Because the use of renewables in industry starts from a low level, the outlook is not yet clear and projections are fraught with uncertainty, both in terms of technology and in terms of quantities. However our analysis suggests that significant potentials and interesting technology initiatives are being pursued in many parts of the world. If deep CO_2 cuts are needed in the coming decades, industry must also contribute. Renewable energy could become a key option to do so. But it will only work if the public and private sectors cooperate. It is proposed to initiate a roadmapping process to develop the vision further, identify promising technology options, explore

Table 4
Share of different forms of renewable energy per industry sector.

	Final energy		Of which biomass 2050		Of which solar 2050		Of which heat pumps 2050	
	2007 [EJ]	2050 [EJ]	[EJ]	%	[EJ]	%	[EJ]	%
Chemical and petrochemical	15.2	40.6	9.1	22	0.0	0	0.0	0
Construction	1.5	2.5	0.2	6	0.0	0	0.0	0
Food and tobacco	6.4	10.0	0.9	9	2.6	26	2.1	21
Iron and steel	16.6	30.5	0.5	2	0.0	0	0.0	0
Machinery	4.6	7.2	0.0	0	1.1	16	1.1	16
Mining and quarrying	2.6	4.1	0.0	0	0.9	22	0.8	20
Non-ferrous metals	4.5	10.6	0.2	1	0.0	0	0.0	0
Non-metallic minerals	11.6	17.1	5.0	29	0.0	0	0.0	0
Paper, pulp and printing	6.8	11.9	6.4	54	0.0	0	0.0	0
Textile and leather	2.3	3.6	0.1	3	0.7	20	0.5	14
Transport equipment	1.5	2.3	0.0	0	0.3	11	0.3	14
Wood and wood products	1.2	3.5	2.4	67	0.0	0	0.0	0
Feedstocks (non-energy)	31.8	49.8	6.9	14	0.0	0	0.0	0
Non-specified (industry)	20.6	32.5	5.7	18	0.0	0	0.0	0
Total	127.1	226.2	37.3	16	5.6	2	4.9	2

the economics and financing needs and develop a policy support programme. Timely action is needed for a transition that will take decades.

A number of issues emerge from this analysis that must be considered in a renewables for industry roadmap:

- Bioenergy and biofeedstock seem key, but industry competes with other sectors for scarce biomass resources. Scenarios for the optimal use of biomass must be elaborated further;
- The interaction between renewable feedstock demand and industry relocation must be analysed in greater detail;
- A switch from heat produced by fossil fuels to electricity from renewables could raise the potentials further, but has not been considered in this analysis;
- Medium temperature steam co-generated in CSP plants and charcoal or similar products for iron making could raise the potential substantially and need to be analysed in greater detail;
- Refrigeration and freezing using solar heat is not attractive today but may piggy-back on solar cooling systems for buildings. This needs to be analysed in greater detail;
- Heatpumps have been identified as an important option but this assumes breakthroughs in the temperature levels supplied;
- A dialogue with industrial energy users and equipment suppliers will be essential in order to agree on feasible pathways. Special attention should be focused on low-cost solutions for developing countries.

6. Conclusions

Renewable energy in industry has not yet received the same attention as in power generation and buildings. We have shown that it is technically possible to substitute half of industrial fossil energy and feedstock use with renewables. Biomass dominates (around 75%), solar heating would be a second key category. A range of technologies will be needed. Certain applications are cost-effective today. Others are still far from commercial application. Important barriers exist in terms of scale, especially for biomass. Bioenergy commodity standards can help to accelerate trade to achieve economies of scale. Lessons can be drawn from ethanol production, collection and distribution.

While low-temperature solar process heat can reach cost-effectiveness, some bioenergy applications will require a CO_2 price and biomass feedstock for synthetic organic materials will require CO_2 prices up to USD 100/t CO_2. Fossil fuel prices and bioenergy prices are the key factors that will determine the economics, and these will depend on a range of factors, notably energy and greenhouse gas mitigation policies across the world. Development of feedstock commodity markets for biomass will be critical.

The present analysis of the long-term potential for renewable energy in industrial applications suggests that up to 21% of all final energy use and feedstock in manufacturing industry in 2050 can be of renewable origin. This would constitute almost 50 Exajoules a year (EJ/year), out of a total industry sector final energy use of around 230 EJ/year in the GEA Scenario M that is used as the baseline projection in this study. This includes 37 EJ/year from biomass feedstock and process energy and over 10 EJ/year of process heat from solar thermal installations and heat pumps. This estimate is considerably higher than other recent global scenario studies. In addition, if a 50% share of renewables in power generation is assumed, the share of direct and indirect renewable energy use rises to 31% in 2050.

Overall, an increase in renewable energy in industry has the potential to contribute about 10% of all expected GHG emissions reductions in 2050. At nearly 2 Gt of CO_2, this represents 25% of the total expected emission reductions of the industry sector. This is equivalent to the total current CO_2 emissions of France, Germany, Italy and Spain, or around one-third of current emissions in the United States. This potential can only be realised, however, if specific policies are developed to create a business environment conducive to private sector investments.

Decision makers are recommended to pay more attention to the potential for renewables in industry. As a next step it is proposed to develop a technology roadmap to explore this potential further. This should include an international dialogue with the private sector (energy users and equipment suppliers) regarding the issues that need to be resolved, a timeline with milestones and financing and policy needs.

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